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Late Holocene climatic fluctuations and soil genesis in southern Patagonia: effects on the archaeological record

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Abstract

Geoarchaeological research conducted at five localities in southern Patagonia and Tierra del Fuego identified a mollisol within late Holocene aeolian and colluvial deposits associated with archaeological material. The mollisol's origin and development are related to an increase in humidity (c. 1000 BP) following an episode of severe drought during the Medieval Warm Period. Corroborating data is supplied from dendroclimatic and pollen studies. A drastic reduction in frequency of artefact distribution recorded at the sites studied corresponds to this pedologic event, suggesting a greater human presence at these sites during earlier, regional-scale arid conditions. However, the paucity of archaeological remains may also be the result of the low resolution of cultural evidence following the pedologic development due to superimposition over previous archaeological deposits.

Keywords: Geoarchaeology; Fuego–Patagonia; Late Holocene soil; Medieval Warm Period; Site formation processes

1. Introduction

Geoarchaeological studies at five localities in southern Patagonia (south of the Santa Cruz River basin) and northern Tierra del Fuego have demonstrated the recurrent presence of a pedologic event in the upper section of widespread late Holocene aeolian and colluvial deposits [10,11] (Fig. 1). The weather in this area is currently defined as cold (+6 °C on average) and semiarid, with an annual mean rainfall of 300 mm. Strong westerly winds buffet the entire region. Phytogeographically, the study area is included in the Patagonian Steppe, with a predominance of grassland, scrub, and heat communities.

On a regional scale, the sequences analysed indicate an active morphogenesis characterised by abundant aeolian deposits after the Middle Holocene, possibly related to arid conditions (see [1,23,30]). Subsequently, there is an interval of pedogenesis represented by a soil that is buried at the archaeological sites under study but remains exposed in other geographically similar areas. The soil's development may indicate an important change in environmental conditions due to the stabilisation of regional aeolian and colluvial systems at that time. Furthermore, there are changes in the distribution of the archaeological record that are linked to this development. This paper examines the morphology, chronology, distribution and paleoclimatic implications of this soil in order to evaluate the role that it played in the regional-scale distribution of the archaeological record.

2. Materials and techniques

The geoarchaeological surveys are part of archaeological research projects carried out in the region to study the evolution of hunter–gatherer populations [4]. The analysis of the environmental dynamics was based on the identification of geoforms, the drawing of stratigraphic profiles, the correlation of litho and pedostratigraphic units and the study of facies. Profiles were described pedologically, and soils were characterised according to *Soil Taxonomy* [34]. Two different methods were used to obtain numerical ages: (1) radiocarbon

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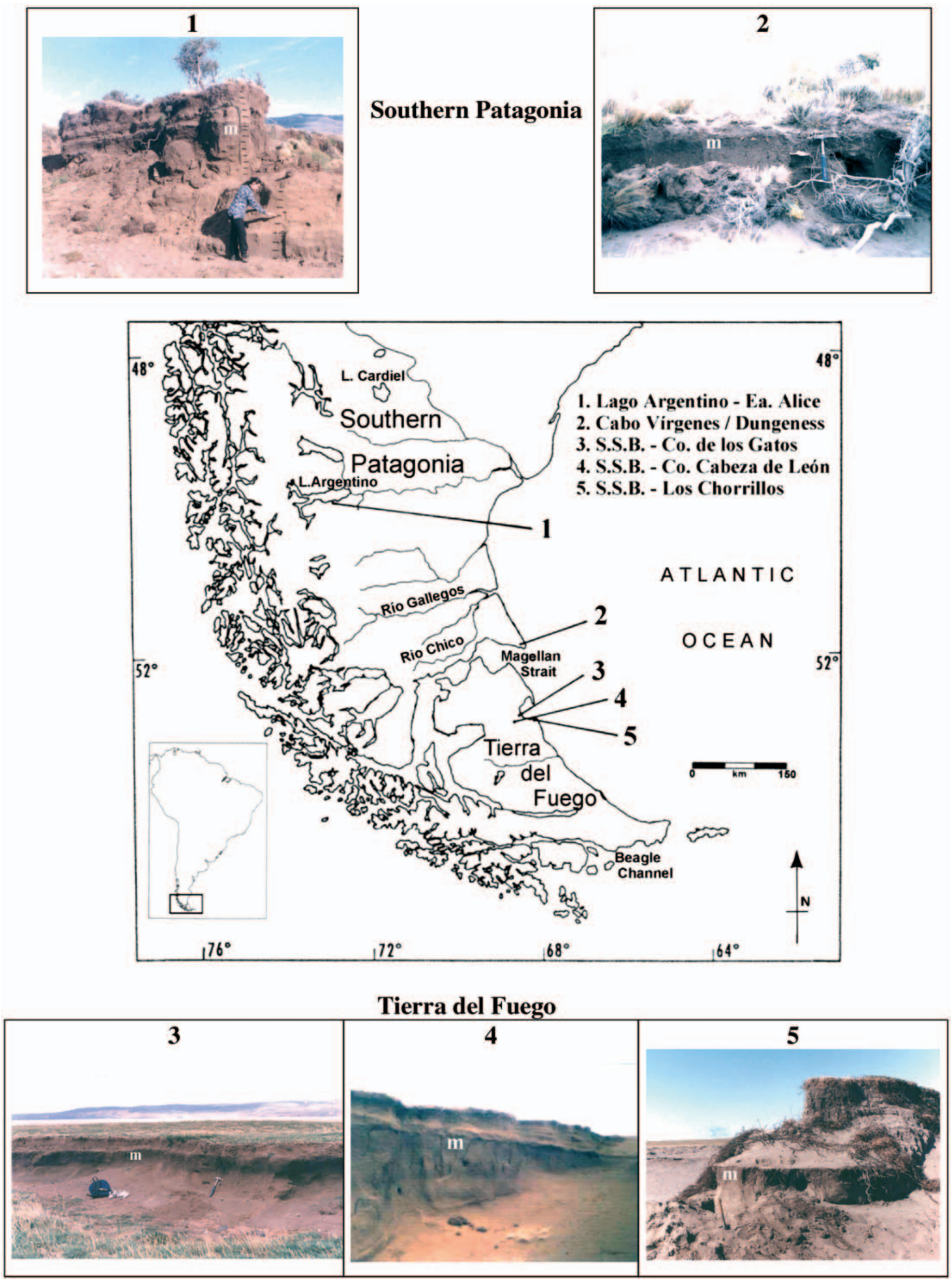

Fig. 1. Map of localities studied and the regional character of the late Holocene mollisol (m).

dating, using both conventional and AMS techniques; and (2) Oxidisable Carbon Ratio (OCR) dating, a method based on the effect of the biochemical degradation of charcoal and soil humic material, measured as a ratio of the total carbon to the readily oxidisable carbon in the sample [12,13]. Texture was determined by sieving and pipetting. The colour of dry soil samples was classified according to the Munsell Soil Color Charts. The representation of organic matter was established by the Walkley–Black method, and pH by the use of a pH metre.

3. Stratigraphy and chronology

Archaeological sequences consist primarily of aeolian and colluvial deposits due to the morphoclimatic

Table 1
Localities analysed in the Fuego–Patagonia region

Locality	Latitude/longitude	Geomorphic context	Archaeological sites
1. Lago Argentino (Estancia Alice)	50°20′S 72°31′W	Dune fields. Sand sheets.	Estancia Alice 1 and 2 [7]
2. Cabo Vírgenes/Dungeness (Magellan Strait)	52°20′S 68°21′W	Dune fields. Sand sheets. Colluvial talus.	CV1 to CV17 [5]
3. Cerro de los Gatos (San Sebastian Bay)	53°15′S 68°34′W	Sand sheets. Colluvial talus.	Cerro "sin nombre" talus, Cerro Las Bandurrias shell midden [11]
4. Cerro Cabeza de León (San Sebastian Bay)	53°18′S 68°33′W	Dune fields. Sand sheets. Colluvial talus.	CL1 and CL4 [3,24]
5. Los Chorrillos (San Sebastian Bay)	53°19′S 68°17′W	Dune fields. Sand sheets. Colluvial talus.	SG1 to SG5 [11,16]

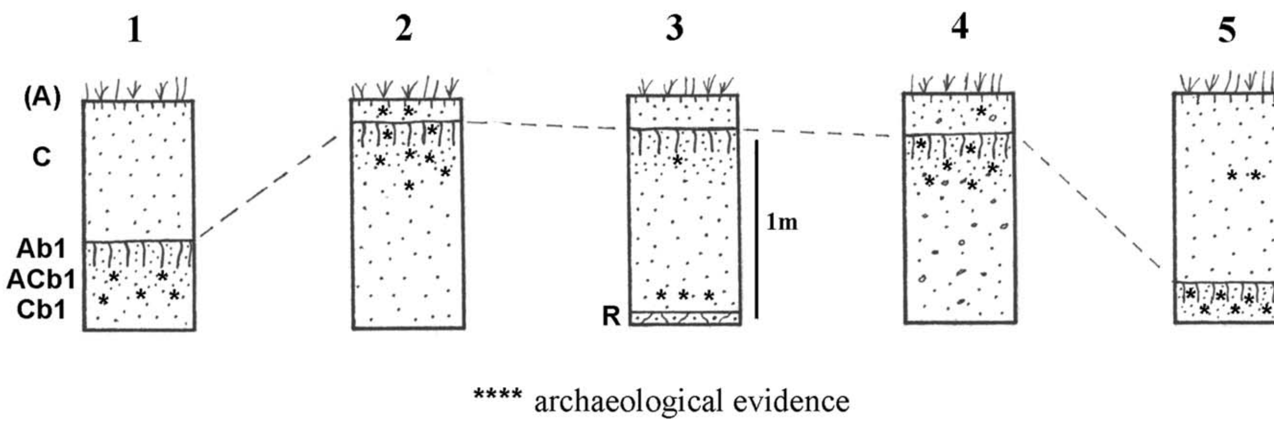

Fig. 2. Representative profiles showing the general sequence at each archaeological locality.

characteristics of the region (Table 1). These sequences present a similar profile in all the localities studied (Fig. 2, Table 2). The profile consists of a lower sandy unit (maximum depth 4 m), crowned by a mollisol (Haploboroll). In many areas that are close to points of erosion the mollisol is buried by a further sandy layer. This second sandy layer often serves as parent material for a poorly developed soil (Cryopsamment).

Archaeological material at the case study sites (i.e. charcoal, lithic and bone artefacts, marine shells, bone remains of mammals, fishes and birds) does not exhibit superficial modification, such as that produced by weathering and wind abrasion, thus indicating the predominance of high rates of sediment accumulation (Table 2).

Two radiocarbon dates of c. 3700 BP from bone collagen (Cerro Cabeza de León), and a maximum date of c. 5700 BP from a cultural shell midden (Cerro Las Bandurrias), were obtained from the bottom of the lowest unit at each location.

The late Holocene soil was dated by radiocarbon and OCR (Table 3). Maximum ages were obtained from materials located in sedimentary units that predate the development of the soil. The dated materials included bone (*Lama guanicoe* or, if indicated, pinnipeds [pp]), charcoal and seashells (*Mytilus edulis* or, if indicated, gastropods [gp]). Minimum ages were obtained by OCR in the AC horizon of the mollisol. These represent the apparent mean residence time (AMRT) [26,33] of the organic matter in this horizon, producing average values which provide a date that tends to be near the beginning of the pedologic event [9].

It is difficult to determine an accurate dating because AMRT values vary according to the depth of the sample, and the lower boundary of the AC horizon is not always clear (typically gradual to diffuse). Higher AMRT values are closest to the beginning of the pedologic event due to the fact that the development of the mollisol constituted a relatively synchronic regional process. Minor chronological variations at a local scale are, however, to be expected.

Maximum ages were obtained from bone remains recovered from the AC and C horizons. Taphonomic variables such as depth, position, size, shape and completeness were used to determine whether these bones were intrusive and, therefore, whether they are reliable indicators of ages prior to the development of the soil. The same criteria were used for molluscs. The earlier dates obtained are considered to be closest to the region-wide origin of the mollisol, which suggests it

Table 2
Description of soils (summary of principal features)

Locality	Horizon	Depth (cm)	Colour (dry)	Texture	Structure	Consistence (dry)	pH	Organic matter—base saturation	Boundary
1	(A)–C	0–100	2.5Y 4/3	S	SG	Lo	7.2	3.3–65%	A&S
	Ab1	100–120	2.5Y 4/2	LS	M	So	6.8		G&S
	ACb1	120–135	2.5Y 4/2	S	M	So	7.1		D&W
	Cb1	135–170+	2.5Y 4/3	S	SG	So	7.1		
2	(A)–C	0–15	5Y 4/2	S	SG	Lo	7.1	7–92%	A&S
	Ab1	15–23	5Y 2.5/1	LS	M	So	7.0		G&S
	ACb1	23–31	5Y 3/1	S	M	So	7.4		D&W
	Cb1	31–60+	5Y 3/2	S	SG	So	7.2		
3	(A)–C	0–20	2.5Y 5/3	S	SG	Lo	7.6	3.6–70%	A&S
	Ab1	20–50	2.5Y 3/2	LS	M	LH	6.8		G&W
	ACb1	50–60	2.5Y 5/2	S	M	So	7.0		D&W
	Cb1	60–120	2.5Y 5/3	S	M	So	7.4		A&S
4	(A)–C	0–35	2.5Y 4/3	Sg	SG	Lo	7.6	4.1–71%	A&S
	Ab1	35–70	2.5Y 3/2	LSg	M	LH	7.0		G&W
	ACb1	70–80	2.5Y 4/2	Sg	M	So	6.6		D&W
	Cb1	80–120+	2.5Y 4/3	Sg	M	So			
5	(A)–C	0–200	10YR 5/1	S	SG	Lo	7.2	7–93%	A&S
	Ab1	200–235	10YR 3/2	LS	M	LH	6.7		G&W
	ACb1	235–275	10YR 5/2	S	M	So	7.5		G&W
	Cb1	275–310+	10YR 5/1	S	SG	So	7.9		

Texture: S (sand); LS (loamy sand); g (with S or LS indicates subordinated small gravel).
Structure: SG (single grain); M (massive).
Consistence: Lo (loose); So (soft); LH (slightly hard).
Organic matter (%)/base saturation (%) [values obtained for Ab1 horizon only].
Boundary: A (abrupt); C (clear); G (gradual); D (diffuse)/S (smooth); W (wavy).

began developing close to, or soon after, cal. AD 1000.

OCR dates were obtained from the top of the A horizon at several locations, and are considered maximum ages for the burial of the soil (Table 4).

Dates appear not to vary in relation to the thickness of the deposit above the mollisol, implying that the beginning of the burial was concurrent at most localities. In the case of the Cabeza de León dunes, however, the soil is older than average, which may indicate an earlier burial at this location.

4. Paleoenvironmental conditions

Chronologically, there appears to be a correspondence between the beginning of the mollisol's development and the presence of climatic anomalies in southern Patagonia that coincided with the so-called Medieval Warm Period (MWP), from the 10th to 12th centuries AD [20]. These climatic fluctuations are present in both southern and northern Patagonia, according to dendroclimatic studies carried out by Stine [35] and Villalba [37,38].

Stine [35] has proposed that a moist period followed severe drought conditions at Lago Argentino and Lago Cardiel based on studies of relict tree stumps of *Nothofagus* sp. from Santa Cruz. The wetter conditions are related to a tree-killing transgression of these lakes. Radiocarbon datings place the date of tree death at the lakes in the range of cal. AD 1051–1226 and cal. AD 1021–1228 respectively [35].

There is also pollen evidence from archaeological sequences at Lago Argentino (sites Charles Fuhr 2 and El Sosiego 4) and Río Chico basin (Don Ariel Cave and Markatch Aike 1 site) that indicates an increase in moisture c. 1500–1100 BP and c. 1200 BP respectively [8,21,22]. At Lago Argentino there is an increase in Poaceae, Cyperaceae and Caryophyllaceae, and a decrease in shrubs [21]. In the Río Chico basin the xeric shrub steppe is replaced at this time by an herbaceous shrub steppe of Graminae and Compositae Tubuliflorae, which likewise indicates greater water availability [8]. The wet conditions detected by these proxy data would have favoured the stabilisation of aeolian and colluvial sediments by plant colonisation, and mark the beginning of the regional-scale soil-forming interval.

Villalba [37,38] has established the following intervals for northern Patagonia based on the dendrochronology of larches (*Fitzroya cupressoides*) from Río Alerce, Río Negro Province: (a) AD 900–1070 cold and moist; (b)

Table 3
Minimum and maximum ages for the beginning of the mollisol's development in southern Patagonia and northern Tierra del Fuego

Localities sampled	Minimum ages (OCR) horizon AC	Maximum ages (conventional and calibrated ^{14}C*) and material dated at horizons AC/C	
1. Lago Argentino (Estancia Alice)	632 ± 18 BP (ACT#3644)	1370 ± 70 BP (bone) (Beta11112231)	1316–1259
	860 ± 25 BP (ACT#3642)	1480 ± 70 BP (bone) (Beta11112232)	1409–1299
	828 ± 24 BP (ACT#4077)		
2. Cabo Vírgenes (Magellan Strait)	617 BP (ACT#3227)	1380 ± 180 BP (bone) (AC1523)	1099–720
	846 ± 25 BP (ACT#3857)	1190 ± 60 BP (bone) (GX-25772)	1171–994
	953 ± 28 BP (ACT#3856)	1050 ± 70 BP (bone-pp) (GX-25276-G)	658–546[2]
	445 ± 13 BP (ACT#3858)[1]	1160 ± 70 BP (bone-pp) (Beta144999)	750–644[2]
	1032 ± 30 BP (ACT#4794)		
	958 ± 28 BP (ACT#4793)		
	887 ± 26 BP (ACT#4792)		
	979 ± 29 BP (ACT#4796)		
3. Cerro de los Gatos (San Sebastian Bay)	772 BP (ACT#2802)	900 ± 115 BP (shells-gp) (AC 1483)	578–432[2]
4. Cerro Cabeza de León (San Sebastian Bay)	620 BP (ACT#2801)	1600 ± 60 BP (bone) (LP-413)	1539–1405
	661 ± 19 BP (ACT#3643)		
5. Los Chorrillos (San Sebastian Bay)	574 BP (ACT#2800)	1070 ± 80 BP (charcoal) (Beta-51997)	1060–924
	980 ± 29 BP (ACT#4079)	1479 ± 95 BP (shells) (AC 1403)	1123–920
		1483 ± 80 BP (shells) (AC 1404)	1105–932
		1420 ± 90 BP (shells) (AC 1484)	1046–887

* 1σ using CALIB 3.0.3. method A [36].
[1] Profile sampled in wet conditions.
[2] If the reservoir effect is taken as 400 years (introduced by the calibration program) then this value is lower than the minimum age. Taphonomic analysis on these marine samples suggests sinsedimentary incorporation. Therefore, a lower reservoir effect value may be considered for this material.

Table 4
OCR dates from the top of the A horizon and thickness of the overlying deposit

Localities sampled	OCR dates (horizon A)	Thickness of overlying deposit
Cabo Vírgenes (Magellan Strait)	120 ± 3 BP (ACT#3854)	70 cm
	144 ± 4 BP (ACT#3855)	160 cm
Cerro de los Gatos (San Sebastian Bay)	170 BP (ACT#2034)	20 cm
Cabeza de León—talus (San Sebastian Bay)	177 ± 5 BP (ACT#4080)	40 cm
Cabeza de León—dunes (San Sebastian Bay)	558 ± 16 BP (ACT#4076)	103 cm
Los Chorrillos (San Sebastian Bay)	170 BP (ACT#2035)	5 cm
	202 BP (ACT#3226)	20 cm

AD 1080–1250 warm and dry (MWP); and (c) AD 1270–1660 cold and moist. Thus, Villalba's studies in northern Patagonia indicate a recurrence of hot and dry conditions during the MWP, while Stine's research south of Santa Cruz demonstrates an increase in moisture in that area (see Table 5). These results should not be considered contradictory but rather are illustrative of the probable atmospheric circulation at that time.

Significantly, climatic simulation models of global warming caused by the greenhouse effect for future conditions in Patagonia predict a rainfall pattern with similarities to extant dendroclimatic data for the MWP [18,19]. The models forecast warmer and drier conditions for northern Patagonia, but greater humidity in southern Patagonia and Tierra del Fuego. Such a coincidence affords an hypothesis worth evaluating. If the MWP was due to a global thermal maximum (of probable solar origin, according to authors such as [17], the correspondence between the data from the simulations

Table 5
Results of dendroclimatic studies and inferred consequences in southern Patagonia

Northern Patagonia [37,38]	Southern Patagonia [35]	
Climatic conditions	Climatic conditions	Inferred consequence
Cold and wet	Severe drought	Morphogenesis
Warm and dry AD 1080–1250	Wet AD 1021–1228	Pedogenesis
Cold and wet	Decreasingly wet	New erosive activity?

and the available climatic-environmental evidence for the period could be tested. This analogy is postulated on the assumption of similar responses within the climatic system. As far back as 1975, Watherald and Manabe's research had already demonstrated that a 2% increase in the solar constant would produce a heating of the troposphere of the same magnitude as a duplication in the CO_2 concentration [39].

In agreement with the simulation results obtained by Labraga [18] and Labraga and López [19], an increase in mean temperature was recorded during the MWP in the waters of the Beagle Channel through $\delta^{18}O$ studies of seashells [28].

Finally, the variables involved in the burial of the late Holocene soil are already being explored at several sites. The burial process appears to be relatively recent (see Table 4). This process may have been the result of climatic factors, such as the occurrence of dry periods after the improvement in environmental conditions detected by dendroclimatic and glaciologic studies (see [1,30,31], for the latter), or was due to anthropic reasons, such as the human impact on the process of erosion and desertification of Patagonia since the 19th century. In the first scenario, climatic constrictions would have resulted in a regional reactivation of the processes of erosion–sedimentation, especially as concerns the so-called aeolian system. In the second scenario, the process would have been more recent and restricted to the sectors of greatest human activity, affecting both colluvial and aeolian deposits equally. These factors may also have acted together or have been superimposed.

5. The archaeological record

Cultural material was recovered frequently from deposits located below the surface of the mollisol, at times in fairly abundant quantities. The upper aeolian and colluvial sediments presented scarce archaeological evidence and were occasionally found in possible resedimentation contexts (i.e. the colluvial sediments at Cerro Cabeza de León). Moreover, artefact distribution frequency was low in the upper part of the pedologic profile. Thus, in spite of presenting a stable surface over several centuries, the mollisol did not receive significant quantities of archaeological material. This would appear to suggest a greater human presence at these sites at some point prior to the soil's development, during the predominance of arid conditions in the region. The difference in artefact frequency may also indicate that the severe drought evidenced by dendroclimatic studies affected the resource distribution and/or concentration in the region, producing variations in the mobility and residential permanence of human groups. This idea was originally put forward by Borrero and Franco [6] in the case of Lago Argentino. They argued that either the already marginal sector was abandoned at this time or a drastic change in circulation and settlement strategies took place, probably linked to water availability.

Such hydrological shifts explain the pattern found in the littoral sectors represented by the sites studied. However, from a geoarchaeological perspective the changes generated in the formation processes of the archaeological record by the emergence of the mollisol may have conditioned the visibility of cultural remains. For example, the preservation potential of bone was less during the pedalogic event than before due to its sensitivity to the effects of intemperisation and decomposing organisms. As a result, it is probable that the reduction in visibility of archaeological material after the beginning of the pedologic development is due to superimposition and poor preservation.

6. Conclusions

The archaeological sequences studied correspond to middle and late Holocene aeolian and colluvial deposits. They exhibit active morphogenesis from c. 5700 BP, related to regional-scale dry conditions. From 1000 BP improved environmental conditions are indicated by the development of a mollisol in aeolian and colluvial systems, which are highly sensitive to changing conditions. The soil is buried where reactivation of erosion–deposition processes occurred (due to natural and/or anthropic causes), including at many of the archaeological sites analysed. On a macro regional scale the mollisol functions as a chronostratigraphic unit, enabling the evaluation of long-term changes in archaeological distributions. The mollisol's emergence in southern Patagonia and Tierra del Fuego was related to an environmental anomaly (i.e. an important increase in humidity) linked to fluctuations during the MWP previously detected by dendroclimatic studies [35]. The pollen record in some localities in southern Santa Cruz also suggests an increase in humidity at that time [8,21,22]. This is consistent with the results of the global heating climatic modelling for the region [18,19].

Distributional changes that occurred during the pedologic event (which lasted many centuries) were detected by comparing the intensity of spatial use in the mollisol deposits and those above (characterised by scarce cultural evidence) with the deposits below this soil (which contained abundant remains). The same pattern is common to the sites on both coasts of the Magellan Strait. In other contexts within the macro region, such as the Río Gallegos and Río Chico river basins, archaeological sites (mainly caves and rock shelters) demonstrate continuous cultural evidence at settlements occupied before and immediately after the MWP [2,14,25,27,29,32]. Recent archaeological research reveals a similar situation at Lago Cardiel [15].

It appears, therefore, that a change in space-use intensity occurred that coincided with environmental

changes in some littoral sectors in the area. However, site formation processes, especially as related to soil formation, may have produced low visibility in the archaeological record. Borrero and Franco [6] suggested dating most of the superficial cultural evidence at Lago Argentino. If this were done at a regional scale by tracing the position of the evidence in relation to the mollisol it would help the analysis of the interaction between climatic conditions and site formation processes, and therefore allow a detailed evaluation of changes in settlement intensity.

This in turn would be a valuable tool for exploring the current visibility of the post-1000 BP record for different contexts in the same region, which would further enable discussion of human responses to environmental changes.

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